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Sample-Specific Conductance Fluctuations Modulated by the Superconducting Phase

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We have studied sample-specific conductance fluctuations tuned by the phase difference between superconducting boundaries, using a two-dimensional electron gas as the phase-coherent normal conductor. In low magnetic fields, $h/2e$ periodic conductance oscillations due to phase-conjugated Andreev reflections are observed with an amplitude $\delta G \simeq 0.10e^2/h$ at $T = 50$ mK. These oscillations are suppressed by a flux of approximately h/e through the interference region. For larger magnetic fields, sample-specific $h/2e$ conductance oscillations are found with $\delta G \simeq 0.005e^2/h$. No indication is found for an intrinsic $h/4e$ periodic superconductor-modified weak localization contribution. [S0031-9007(96)00275-X]

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Electron transport in a disordered phase-coherent conductor, small compared to the phase-breaking length l_φ but larger than the elastic scattering length l_e, is presently understood as a result of quantum interference of scattered electron waves [1]. The interference pattern and hence the conductance is changed by a change in magnetic flux of h/e or a change in Fermi energy over a scale of the Thouless energy. For a specific sample, the fluctuations in the conductance are reproducible and have amplitudes close to the universal magnitude $\delta G \simeq e^2/h$, reached at temperatures below the Thouless energy, while at finite temperature thermal averaging leads to smaller values. A particularly clear demonstration of these conductance fluctuations is found in ring-shaped conductors. Electron waves are scattered through both arms of the ring and the amplitude of the electron waves depends on the phase shift due to the enclosed magnetic flux through the ring, leading to Aharonov-Bohm oscillations with period h/e. In addition, a weak localization contribution due to the interference of time-reversed paths exists with period $h/2e$.

Since phase coherence is a crucial ingredient of mesoscopic conductors, an interesting question is the possible influence of the macroscopic quantum phase of a superconductor on the conductance fluctuations of a disordered normal conductor [2]. This question has been addressed in several theoretical papers [3], exploiting the transfer of the macroscopic superconducting phase at normal-superconductor (NS) interfaces by Andreev reflection [4]. It is concluded that the ultimate magnitude for the conductance fluctuations is doubled to $\delta G \simeq 2e^2/h$. Much earlier [5], it was also predicted that time-reversed trajectories involving scattering from two superconductors would result in $h/4e$ oscillations in the conductance as a function of the superconducting phase difference.

Experimental observation of Andreev-mediated conductance fluctuations requires disordered samples with lengths smaller than l_φ. A recent attempt to get access to this regime is the experiment of de Vegvar *et al.* [6], who studied a four-terminal normal conductor clamped between two superconducting electrodes, which were connected to a series array of Josephson junctions used to vary the macroscopic superconducting phase difference $\Delta\phi$. Although the samples were not small compared to l_φ, the conductance is reported to vary in response to a change of $\Delta\phi$. This variation is different for the two samples studied, suggesting sample-specific conductance modulation with an amplitude of $10^{-3}e^2/h$. Unfortunately, the technique used in the experiment allowed only small variations of $\Delta\phi$ in contrast to the Aharonov-Bohm normal metal rings in which many periods could be studied.

In the experiment reported here we have made several crucial improvements, which allows us to present conclusive evidence for Andreev-mediated conductance fluctuations. First, we have chosen short samples with lengths close to l_φ. Second, by using a low electron density two-dimensional electron gas (2DEG) for the normal conductor a smaller number of populated quantum channels is used, which increases the contribution of sample-specific over ensemble-averaged behavior. Third, the superconducting phase difference is changed by using a superconducting loop allowing us to study many periods of conductance oscillations and to observe unambiguously the transition from ensemble-averaged to sample-specific behavior.

We have designed an interferometer by coupling an interrupted superconducting loop to a T-shaped 2DEG (see Fig. 1). The phase difference between the superconductors can be controlled by an applied magnetic flux. Alternatively, an applied dc current flowing through the loop changes the phase difference via the induced magnetic field. We used an InAs/AlSb heterostructure because of the absence of a Schottky barrier between the superconductors and the 2DEG in the 15 nm InAs layer

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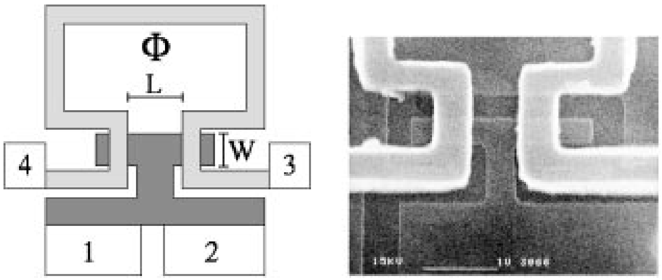

FIG. 1. Sample layout. The left-hand panel shows a schematic picture of a T-shaped 2DEG with an interrupted niobium loop. The contacts (1) and (2) are connected to the T-shaped conductor and (3) and (4) are connected to the superconducting niobium loop. The dimensions are $L \simeq 0.7\ \mu$m and $W \simeq 0.3\ \mu$m. The right-hand panel shows a scanning electron micrograph of the actual device.

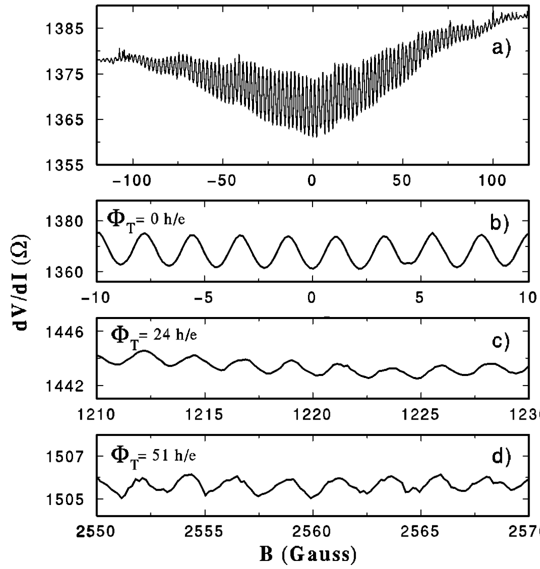

FIG. 2. (a),(b) The magnetoresistance $R_{13,24}$ in low magnetic fields. (c),(d) Two traces in higher magnetic fields at $T =$ 50 mK. The flux Φ_T indicates the number of flux quanta h/e ($\simeq$ 50 G) through the total T-shaped 2DEG including the Meissner effect.

underneath. The 40 nm AlSb top layer was removed prior to processing. Patterning of the 2DEG was done using conventional *e*-beam lithography and wet etching. The transport properties of the 2DEG in a wet-etched InAs channel are $n_s \simeq 1.3 \times 10^{16}$ m^{-2} and $\mu_e \simeq 1.6$ m^2 V/s, resulting in electron mean free path $l_e \simeq 0.3\ \mu$m. The 50 nm Nb superconducting electrodes were deposited after *in situ* Ar cleaning of the exposed InAs surface [7]. The length L of the T-shaped 2DEG between the Nb electrodes is 0.7 μm and the width W is 0.3 μm, resulting in diffusive transport in this channel. This corresponds with a Thouless energy $E_T = \hbar v_F l_e/L^2 \simeq 0.3$ meV. The critical temperature T_c of the Nb loop is about 7.5 K and the critical current is larger than 1 mA. We have checked that the Nb loop remained superconducting for all applied magnetic fields. As a consequence, the Nb electrodes had the same electrochemical potential.

We have characterized three devices at a temperature of 50 mK using standard 4-probe ac lock-in techniques with filtered leads. We present the data of one device. The current is injected by one of the contacts (1,2) and extracted by one of the other contacts (3,4). The voltage difference is measured between the two remaining contacts. The zero-bias resistance $R_{13,24}$ is approximately 1370 Ω, which corresponds well with a geometrical estimate of four times the resistance per square. Furthermore, the energy dependence of $R_{13,24}$ shows a decrease of 4.5% below 2.0 mV due to the onset of Andreev reflection. The magnitude of the decrease is 20% of the estimated Sharvin resistance, indicating that the NS interface is indeed highly transparent ($T_{\rm NS} \approx 0.7$) [8]. Since the decrease in the resistance starts close to the niobium energy gap ($\Delta_{\rm Nb} \sim 1.3$ meV), the energy-relaxation length $l_{\rm in}$ is concluded to be comparable to the size of the T-shaped 2DEG.

Figure 2 displays the observed magnetoresistance. The effect of the applied magnetic field is twofold. First, the phase difference $\Delta\phi$ between the two superconducting electrodes is changed according to $\Delta\phi = 2\pi\Phi/\Phi_0$, where Φ is the applied flux through area A ($\approx$10.3 μm^2) confined by the Nb loop and the T-shaped 2DEG and $\Phi_0 \equiv h/2e$ [9]. Second, the magnetic field penetrates the T-shaped 2DEG. Because of the Meissner effect this magnetic field is enlarged by a factor $\sim(L + D)/L$, where D is the width of the Nb wires ($\approx$0.5 μm). In Fig. 2(a) the magnetoresistance $R_{13,24}$ at low B is shown. Figure 2(b) shows a closeup of the low-field oscillations with an amplitude $\delta G_{\rm qp} \simeq 0.10e^2/h$ and with a period $h/2e$, which corresponds within 10% with the geometrical expectation ($h/2eA$). These oscillations are analogous to those found in other SNS interferometers [10], and result from (multiple) phase-coherent Andreev reflections [11]. Since they are independent of the specific impurity configuration, they survive ensemble averaging. These quasiparticle interference oscillations are expected to average out when two flux quanta Φ_0 penetrate the upper part of the T-shaped 2DEG [12]. In our device this occurs at approximately 120 G, which corresponds well with $2\Phi_0$ through the upper part of the T-shaped 2DEG [area $\simeq W(L + D)$].

Remarkably, the oscillations do not completely disappear for magnetic fields corresponding with several flux quanta through the total T-shaped 2DEG, as one can see in Figs. 2(c) and 2(d). The typical amplitude of these high-field oscillations is $\delta G_{\Delta\phi} \simeq 0.005e^2/h$ and the period is $h/2e$. By averaging over one period a fluctuating background resistance is obtained with $\delta G_{\rm CF} \simeq 0.02e^2/h$. In Fig. 3(a), the data are shown after subtracting the fluctuating background resistance, leaving the $h/2e$ oscillations. The crossover from low-field quasiparticle oscillations to

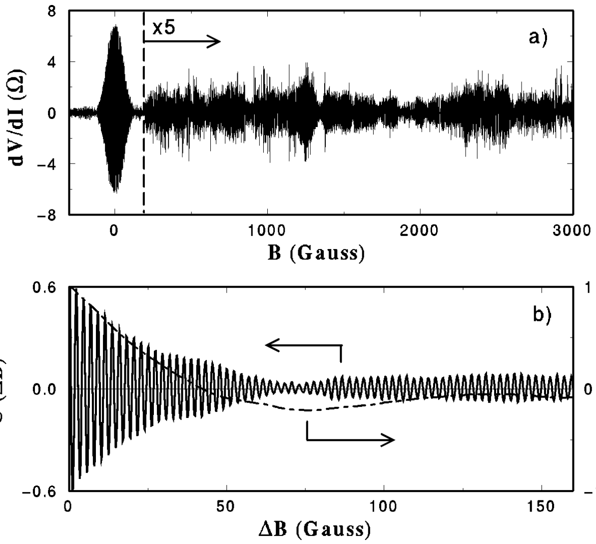

FIG. 3. (a) Magnetoresistance $R_{13,24}$ minus the background resistance at $T = 50$ mK. (b) Autocorrelation function $C(\Delta B) \equiv \langle \delta R(B) \delta R(B + \Delta B) \rangle / \langle \delta R(B)^2 \rangle$ between 200 and 3000 G for the Andreev-mediated conductance oscillations of the trace shown in (a) (solid line) and for the fluctuations in the background resistance (dashed line).

high-field oscillations around 120 G is evident. The envelope of the high-field oscillations clearly fluctuates. We have analyzed the autocorrelation $C(\Delta B)$ of both the high-field oscillations and the fluctuations in the background resistance for $B \geq 200$ G [see Fig. 3(b)] [13]. A shift in the magnetic flux by an amount of h/e through the phase-coherent interference region should about halve the correlation of both the high-field oscillations and the fluctuations in the background resistance. In Fig. 3(b) this occurs around 30 G. A flux quantum h/e through the T-shaped 2DEG corresponds to about 50 G. This difference could indicate that the total phase-coherent interference region extends outside the T-shaped 2DEG. Since both the high-field oscillations and the fluctuations in the background resistance show the same decay in the autocorrelation, we attribute these high-field oscillations to be sample-specific conductance fluctuations tuned by the phase difference across the two superconducting boundaries.

The magnitude of δG_{CF} is lower than e^2/h, which we ascribe to our specific geometry. Furthermore, since $\delta G_{\Delta\phi} \approx 0.25 \delta G_{\mathrm{CF}}$, we believe that the boundary conditions imposed by the superconductors cannot fully modulate the conductance fluctuations. The other two nominally identical devices showed a similar behavior at low magnetic fields. However, the amplitude and phase of both the high-field superconductor-modulated conductance oscillations and the fluctuations in the background resistance were uncorrelated, illustrating the sensitivity of the effect to microscopic differences in the sample.

Closer inspection of Figs. 2(a) and 2(b) around zero magnetic field reveals a second harmonic contribution (with period $h/4e$) with an amplitude $\delta G \simeq 0.01 e^2/h$. However, we believe that this is not a new type of oscillation, but that they are related to the low-field $h/2e$ oscillations. The presence of a circulating supercurrent $I_c \sin \Delta\phi$ and a finite self-inductance L_{loop} generates an additional flux, which destroys the linear relation between applied magnetic field and superconducting phase difference [14]. The low-field conductance oscillations will therefore look like a distorted sinusoidal modulation, yielding higher order harmonic contributions. The maximum deviation is $\alpha = L_{\mathrm{loop}} I_c / \Phi_0 \approx 0.023$. By passing a dc current through the Nb electrodes and simultaneously measuring the quasiparticle oscillations, we have determined L_{loop} to be 20 pH. The amplitude of the $h/4e$ oscillations can thus be explained with the above mechanism if the critical current I_c is about 2.5 μA [15]. However, in our geometry I_c cannot be measured directly. Therefore, we cannot rule out an intrinsic nonsinusoidal phase dependence of the conductance, as predicted in Ref. [11].

The energy dependence of the amplitude of the low-field quasiparticle oscillations is determined by measuring at finite voltages; see Fig. 4(a). The zero-phase conductance $G(\Delta\phi = 0)$ remained a maximum for all applied biases. The amplitude of the quasiparticle oscillations is roughly halved for an applied bias of $eV_{\mathrm{dc}} \sim E_T \simeq 0.3$ meV, where the phase conjugation of electrons or holes is lost. The decrease in amplitude for $V_{\mathrm{dc}} \leq 0.15$ mV could be a signature of the reentrant behavior of the differential resistance, since for energies below E_T the effect of phase-coherent Andreev reflection is shown to be reduced [11]. In Fig. 4(b), the amplitude of the $h/4e$ component

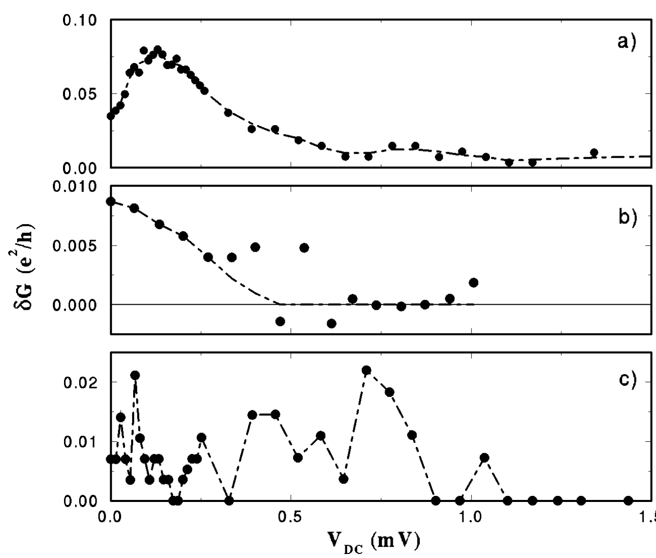

FIG. 4. Amplitude of the modulation in the resistance $R_{13,24}$ as a function of the applied dc-bias voltage V_{dc} at $T = 50$ mK for (a) the low-field quasiparticle oscillations, (b) the $h/4e$ component [obtained by fitting (a) with a $\sin 2\phi$ component] and (c) the high-field oscillations (around 320 G). The dotted line is a guide to the eye.

is plotted. In principle a fraction of these $h/4e$ oscillations could still be due to superconductor modified weak localization. Especially for biases higher than the Thouless energy, when the circulating supercurrent diminishes, the superconducting-phase modulated weak localization contribution could become visible, because it should, in first order, survive energy averaging [16]. We conclude that if the superconducting-phase modulated weak localization contribution exists in this regime $eV_{\mathrm{dc}} > E_T$, they have a magnitude smaller than $\delta G \sim 10^{-3}e^2/h$ (based on the fitting error). Figure 4(c) displays the energy dependence of the high-field $h/2e$ oscillations. A clear distinction between the low- and high-field oscillations is that the high-field oscillations persist to higher energies. We were not able to measure accurately enough [17] to confirm that the conductance fluctuations change on a scale of E_T.

In conclusion, we have studied two types of conductance oscillations tuned by the phase difference between two superconducting boundaries attached to a T-shaped 2DEG. The low-field quasiparticle interference oscillations are destroyed by a flux quantum h/e through the interference region, leaving in higher magnetic fields sample-specific conductance oscillations.

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Note added.—We recently studied the phase dependence of the multiterminal transport in cross-shaped 2DEG-superconductor interferometer. In this case the major contribution to the nonsinusoidal phase dependence was shown to be intrinsic, and related to the modulation of the reentrant proximity effect [11].

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[12] In disordered conductors with $W \gg L$ the quasiparticle interference takes place only between trajectories originating from the same position along the superconducting boundary (W), leading to a Fraunhofer pattern for the envelope of the oscillations: $|\sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)|$. One could argue that if $L \geq W$ the quasiparticle interference occurs between random points along the superconducting boundary, resulting in an amplitude for the quasiparticle oscillations of $\sin^2(\frac{1}{2}\pi\Phi/\Phi_0)/(\frac{1}{2}\pi\Phi/\Phi_0)^2$; thus the first minimum is reached when $\Phi = 2\Phi_0$.

[13] Because of the finite number of uncorrelated segments ($\sim$100), the autocorrelation function shows statistical fluctuations for shifts larger than the correlation field.

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[15] An I_c of $\sim$2.5 μA is typical for a junction with a width of 1 μm. Note that there is, apart from the T-shaped 2DEG, also a contribution to the supercurrent from the region above the T-shaped 2DEG.

[16] The theory of Ref. [5] is valid when the thermal length $\xi_T \approx \sqrt{\hbar D/kT} \leq L$, but in our device $\xi_T \geq L$ for all temperatures below T_c. However, if the applied voltage V is increased, the role of ξ_T will be taken over by ξ_V ($\approx \sqrt{\hbar D/eV}$). For $eV_{\mathrm{dc}} \sim E_T$, the regime $\xi_V \leq L$ is reached.

[17] Especially the high-field $h/2e$ oscillations were found to show time-dependent fluctuations.